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Vertue, a green orbital module to meet the growing demand for in-orbit operations

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Abstract

Vertue is an innovative green orbital module under development in Finis Terrae, conceived and designed to meet the demand for in-orbit operations, leveraging access to space through the Vega family of European small launchers. The objective is to enable future applications in all space sectors, ranging from Telecommunications to Earth Observation, Launch Systems to Navigation, Space Exploration to Lunar and Martian Infrastructures, Atmospheric Re-entry to In-Orbit Services. In this manuscript the architecture of Vertue will be presented, the main performance parameters analysed, and all the possible applications discussed, emphasizing the novelty of the technical solution in the space transportation arena.

1. Introduction

Over the past two decades, initiatives from commercial and private actors have decentralized space, propelling a new-born space economy, where novel economic activities and opportunities blossom aplenty. Among them, in-orbit operations are long set to disrupt the space ecosystem in a foreseeable future [1]. In the wake of this new-space momentum, the number of objects orbiting Earth is skyrocketing at a dramatic rate each year [2]. Mega constellations (Starlink, Kuiper, OneWeb among those in service) are crowding an already congested low-Earth environment. In this regard, active debris removal (ADR) as part of in-orbit operations might answer the urgent call for long-term sustainability. Focusing on the geostationary belt, life-extension services by means of refuelling would maximize the return from GEO missions of a significant number of satellites which will reach EOL over the next decade. As announcements for new generation launch systems adopting a two-stage-to-orbit architecture increase, so does the need for Last Mile Delivery (LMD) services. ADR, life-extension, and LMD services represent addressable markets with expected revenues in the order of billions of US Dollars (USD) by the half of the thirties [3]. In-space manufacturing and assembly, satellite inspection and maintenance, tugging and towing, payload download services are only another handful of possibilities in the realm of in-orbit operations, in and beyond Earth orbit [4]. Cislunar and Martian activities fostering a deep space economy are in the plan [5]. Overall, in-orbit operations are an emerging business opportunity, that anticipates an already booming market.

Finis Terrae, an innovative start-up based in Rome, is eager to seize this opportunity. An orbital propulsion module, Vertue OPM (Orbital Propulsion Module), is under development to meet the demand for in-orbit operations, leveraging access to space through the Vega family of European small launchers. The present paper reviews the up-to-date space launch market analyses focusing on small lift vehicles, thereby identifying needs and suitable use cases. Within the standard of the Vega Space System– a modular evolution of Vega capable of tailoring the launcher to different missions– the Vertue module will enable orbital operations, providing propulsion to in-orbit servicing and deep space missions. The design of the module, based on advanced composite materials and a smart arrangement of the tanks with the propulsive subsystems, results in a structural efficiency parameter up to 60% better when compared to current competitors in the market. This translates in several hundred kilograms more payload mass for the same velocity increment ΔV. The propulsive unit, a liquid rocket engine burning a green combination of propellants, may be simply disconnected and replaced, thus providing maintainability.

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2. Reference scenario

The Space Economy represents a rapidly growing sector on a global scale. According to the most conservative estimates by Morgan Stanley ([6]), the market will surpass a value of over $1 trillion annually by 2040.Despite uncertainties arising from the current geopolitical situation and the aftermath of the pandemic, the majority of analysts agree on a compound annual growth rate (CAGR) of just under 7% in the short term ([7]).

The growth of the global space economy market is driven by the proliferation of applications and commercial actors in the sector, which in many cases have replaced government space agencies due to reduced costs, higher risk appetite, and shorter time to market access.

In recent years, the market has been supported by increased government funding for space programs worldwide, the development of space economy infrastructure, the rising demand for launches, the increased demand for satellites, and renewed interest in space exploration. However, the growth will not be uniform, and the emergence of competitive players in the market could lead to the transformation of certain sectors of the Space Economy into commodities, controlled by a few global players.

In the coming years, we will witness the consolidation of a trend that sees the progressive replacement of geostationary orbit platforms for broadcasting applications in favour of constellations, often large ones, composed of smaller satellites in Low Earth Orbit (LEO) for broadband communication, Earth observation, both for commercial and scientific purposes, as well as defence applications. Additionally, the growth and consolidation of satellite constellations for navigation, primarily located in high-energy Medium Earth Orbit (MEO) (e.g., semi-major axis of 29,500 km and inclination of 56°), are anticipated. In subsequent generations, these constellations may incorporate navigation and data relay applications among space assets. The deployment and maintenance of such constellations, based on larger platforms than those of Galileo, will necessarily require transport services that allow a reasonable deployment time to avoid efficiency reductions or service interruptions to users.

Finally, there is an anticipation in the proliferation of constellations for the distribution of quantum encryption keys, as well as increased interest in orbital construction of infrastructures (logistics and space infrastructures). This will lead to an increased demand for high-energy orbital transfer services (kick-stages), for example, to transport assets released in LEO to other orbits such as MEO, Geostationary Orbit (GEO) (for geostationary applications at 36,000 km and 0° inclination), lunar or Martian orbits.

The demand for orbital services will thus constitute a significant fraction of the space economy starting from the end of this decade. Orbital services can be commonly classified into several categories, including:

- Last Mile Delivery, which involves transferring individuals from an initially grouped satellite constellation to individual orbits through orbital plane, altitude, or anomaly changes.
- Spacecraft Refuelling, which extends the operational life of an orbital asset by providing it with propellant or other materials or components.
- Spacecraft Repair, which allows for the replacement or maintenance of components to extend or adapt the operational life of an orbital asset.
- Active De-orbiting, which encompasses the capture, deorbiting, or relocation to graveyard orbits of space assets at the end of their orbital life.
- Download, which involves the secure transfer of payloads (spacecraft, materials) from Earth orbit to the ground through re-entry shuttles.

This set of space transportation services defines the contours of the industrial challenge in the Space Economy at the end of this decade. Given the democratization of space and the emergence of commercial actors (especially in Europe and the United States), competition in this sector is expected to be the central element of the market. It is also crucial to note that there is currently no global player capable of offering this kind of service.

In this scenario, the creation of a highly performant and reliable propulsion module represents a fundamental challenge for the new Space Economy, with the ultimate goal of filling a current gap in the offering of upper stages and ensuring a significant competitive advantage over future competitors.

The high flexibility in meeting the aforementioned market demands, combined with significantly higher efficiency compared to currently available upper stages on the market, makes the system herein proposed – the Vertue OPM - a

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world-class solution that is technologically advanced and capable of securing a leadership position in the sector at both national and global scales.

3. System architecture

The Finis Terrae project provides an ambitious yet highly effective response to the industrial challenge of orbital space transportation. The project is currently in its early development phase, with several mission analyses focused on the need for orbital propulsion modules to complete the European or global Space Transportation Service chain in the next decade.

Compared to traditional space propulsion systems, the novelty in the Vertue OPM is based on the original combination of four technological pillars with varying levels of maturity:

1. Throttleability. The main thruster can adjust thrust up to 4 kN, fed by electric pumps and propelled by a greener (i.e., less toxic) combination of propellants compared to the established Hydrazine/Nitrogen Tetroxide pair.
2. Integrated attitude orbital control system. The pumps and the tank feed propellants both to the main engine and to the attitude and orbit control thrusters.
3. Low-Pressure Toroidal Tank (LPTT), made up of thermoplastic composite material. The implication of points 2. And 3. is two-fold:
    a. Higher structural efficiency, because of the optimized distribution of tank volume and the lightweight structure, arranged so as to transfer the flight general loads.
    b. Higher performance, i.e., increased payload mass for the same total impulse.
4. The Micro-Acceleration capture Device (MAD), for which a patent has been filed. The MAD(s) collect the propellant to the tank outlet in microgravity environment.

The architecture identified for the Vertue OPM is depicted in Figure *1*. and includes:

- a bi-propellant rocket engine, combusting green liquid propellants.
- electrical pumps powered by batteries.
- a thrust vectoring system comprising two electromechanical actuators allowing gimballing.
- two or more clusters of attitude control engines powered by the same fuelling device as the main engine.
- a propellant pressurization subsystem for the main tanks.
- two propellant tanks integrated into a single structure, featuring mechanical interfaces for the launch vehicle, payload, propulsion assembly, attitude control engines.
- the avionic canister, integrated in the tank structure, compact and easily removable for inspection.
- two propellant capture devices (MAD) for microgravity conditions.

The architecture is completely modular and allows adaptation to propellant loading levels varying from 200kg to over 2000kg, depending on the mission and the interface with the launch vehicle (e.g., Vega C, Vega E, Ariane 6, Falcon 9 etc.) with standard adapters of type 937, 1194 or 1666. The propellant loading and the reference dimensions for each configuration of the Vertue OPM are reported in Figure *2* and Table *1*.

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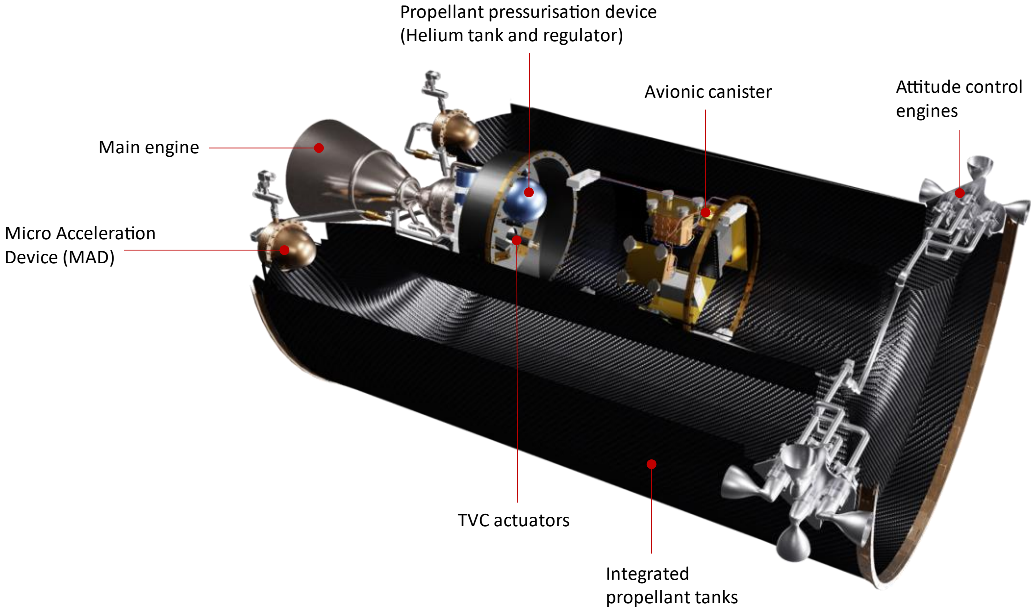

Figure 1: Vertue OPM, architecture.

Table 1: Overall dimensions and propellant loading for the Vertue OPM.

OPM	Φ D1 [mm]	H1 [mm]	H2 [mm]	Volume [l]	Propellant mass [kg]	Structural efficiency K_s
OPM-1	937	675	870	321	**385**	0,21
OPM-1b	937	800	995	423	**507**	0,18
OPM-2a	1194	800	995	744	**893**	0,13
OPM-2b	1194	1000	1195	960	**1152**	0,11
OPM-2c	1194	1800	1995	1728	**2073**	0,08
OPM-3	1666	950	1145	1616	**1939**	0,09

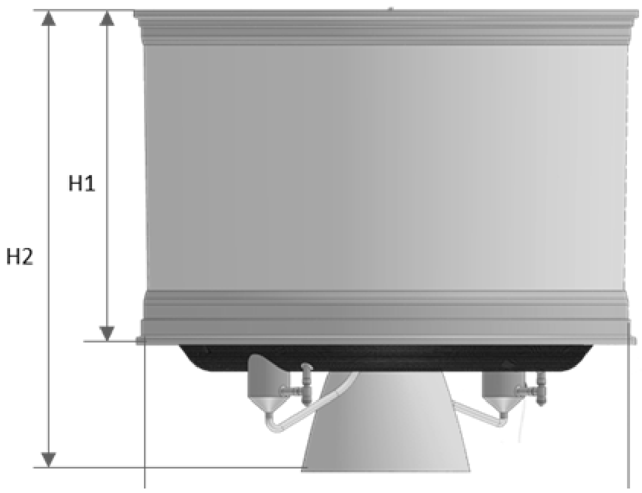

Figure 2: References dimensions

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4. Performances

The combination of the proposed architecture and the technologies of the various elements presented makes it possible to obtain results in terms of structural efficiency that have never been obtained for an orbital module. A structural efficiency is computed as follows:

$$K_s = \frac{m_s}{m_s + m_p}$$

in which:

- m_s is the inert mass of the module, including structures and avionics.
- m_p is the propellant loading.

The computed values of structural efficiency for the OPM family, are reported in Table *1*. The structural efficiency is plotted against the propellant loading in Figure *3*, comparing the results for the OPM family with several reference in the market.

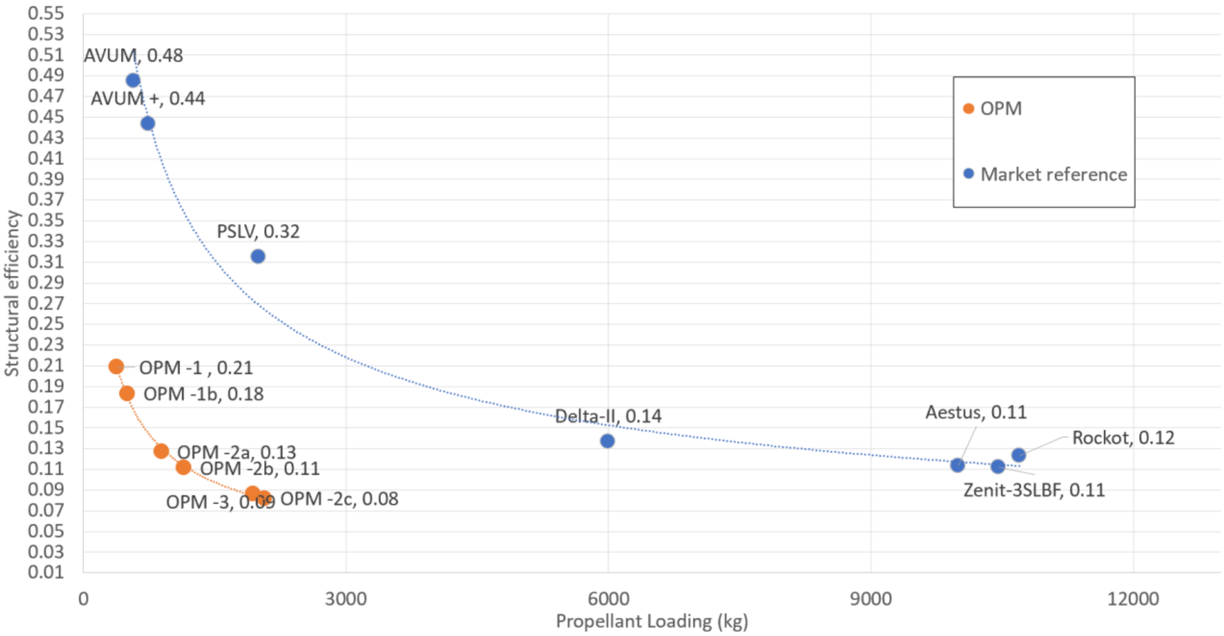

Figure 3: Structural efficiency of Vertue OPM compared to the state of the art.

One can observe that:

- for the same mass of propellant loaded, the structural coefficient obtainable with OPM is significantly lower than that of the main competitors in the market.
- For the same total impulse, the Vertue OPM provides a significantly lower inert mass and, consequently, a heavier payload compared to other propulsion modules or high stages of launch vehicles. For instance, for certain missions launched with Vega E, the payload increase can be as much as 35%.
- The better performance enables missions considered out of reach for medium-small launchers, such as
  - the launch of a satellite for the Galileo navigation constellation in MEO orbit (29500km half-axis at 56° inclination)
  - exploration missions and, in general, In Orbit Service (IOS) missions, when suitably integrated with other modules.

The Vertue OPM, when developed in accordance with technical, cost and market availability targets, could become the world reference in the sector.

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5. Applications and use-cases

Finis Terrae aims to develop an innovative propulsion system that can provide a competitive response to the demand for space transportation services. This propulsion system, the Vertue OPM, utilises green propellant chemical propulsion and integrates both main propulsion and attitude control functions, allowing optimal loading of propellants between 200kg and over 2000kg. The Vertue OPM is compatible with Payload Adapters and standard flight environments of Western launch vehicles, particularly those of the Vega family.

The Vertue system could enable evolutions and new applications in the following space sectors:

- Telecommunications: the Vertue OPM can enable the transfer of telecommunications satellites from low orbit (LEO) to geostationary orbit (GEO), as well as Last-Mile Delivery (LMD) services with any launcher.
- Earth Observation: the Vertue OPM can be used as a Kick-Stage to provide acceleration to the payload post-separation from the launcher or for the deployment of constellations of small Earth observation satellites.
- Launch Systems: the Vertue OPM can easily be used for Kick-Stage services to provide final acceleration to the payload once it has been released from the launcher's main stage, and Last-Mile Delivery with any launcher, to transfer individuals from a group of satellites initially in orbit together, to individual orbits through orbital plane change, altitude or anomaly manoeuvres.
- Navigation: the Vertue OPM can transfer Galileo satellites for navigation from LEO orbits to MEO orbits.
- Space Exploration: the Vertue OPM can provide a speed boost of about 3.5 km/s to payload larger than 650 kg, paving the way for numerous future space missions.
- Lunar Infrastructure: the Vertue OPM can be used as a Lunar Shuttle, for orbital missions around the Moon, or as a Lunar Lander, for landing and transporting useful materials on the lunar surface.
- Mars infrastructure: the Vertue OPM can be used to carry out the so-called Small Mission to Mars, a mission to the planet Mars characterised by a reduced size and complexity compared to the large interplanetary missions carried out so far, aimed at sending a small orbiter or lander or a probe equipped with scientific instruments to explore the planet.
- Atmospheric Re-entry: the Vertue OPM can act as a propulsion module for Space Rider, thus ensuring the possibility of atmospheric re-entry.
- In-Orbit Service: the Vertue OPM can contribute to activities within the IOS framework, with particular reference to the following sub-categories of services:

    - Last Mile Delivery: this involves the transfer of individuals from a group of satellites initially in orbit together to individual orbits. This is achieved through orbital plane, altitude or anomaly change manoeuvres.
    - Spacecraft Refuelling: this operation allows the operational life of an orbital asset to be extended by providing it with additional propellant, materials or components.
    - Spacecraft Repair: This operation allows the replacement or maintenance of components to extend or adapt the operational life of an orbital asset.
    - Active De-orbiting: this is a service that includes the safe capture and removal of space assets at the end of their orbital life, moving them into graveyard orbits or causing them to de-orbitalise and disintegrate in the Earth's atmosphere.
    - Active Debris Removal: this is a service that includes the capture and safe removal of space debris orbiting the Earth.
    - Orbital Plane Change: the operation to change the orbital plane of a spacecraft.
    - Download: this operation involves the safe transfer of payloads from Earth orbit to the ground via re-entry shuttles.

The possible use cases described are summarised in Table *2*, which also shows the main performance parameters associated with each use case.

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Table 2: Examples of use cases for the Vertue OPM orbital module.

ID	Use Case Description
1	Transfer of broadcast satellites from LEO elliptical orbit to GEO orbit
2	Deployment of Earth observation satellites from LEO elliptical orbit
3	Last-Mile Delivery with the Vega launcher, to transfer individuals from a group of satellites initially released jointly into orbit, to individual orbits through orbital plane change maneuvers, altitude or anomaly.
4	Transfer of Galileo satellites for navigation from LEO orbits to MEO orbits.
5	Kick-Stage, providing a ΔV speed increase of about 3.5 km/s to payload larger than 650 kg for future space missions.
6	Lunar Shuttle, to transfer payloads from Earth orbit to lunar orbit
7	Lunar Lander, to deliver payloads to the lunar surface
8	Small Mission to Mars, to transfer payloads from Earth orbit to Mars orbit
9	Atmospheric Re-entry: Vertue can act as a propulsion module for Space Rider
10	In-Orbit Servicing, including robotic arm applications

6. Results

In this section, the available payload mass is computed as a function of the ΔV and as a function of the structural efficiency for the reference missions reported in Table *3*, under the following assumptions:

1. The orbits specified as starting point are taken from the relevant launcher's user's manual, according to the required ΔV available from open literature. Hence, for example, the GTO was chosen for Ariane 6-2 despite the availability of an optimised lunar transfer orbit in the manual. Therefore, the starting points are not the optimum, but are chosen to demonstrate the capability of Vertue OPM to perform the selected missions.
2. The inert mass does not include the weights of solar arrays (if needed) and robotic arm, but includes the mass of structure, avionics, propulsion system and AOCS.

Table 3: Reference missions

Mission	Starting point	Target	Required ΔV, km/s	Launcher	Reference
IOS	LEO (@ 500 km, 45°)	LEO operations	1.0÷2.5	Vega C	
	LEO (@ 250 km, 51.6°)	LEO operations	1.0÷2.5	Ariane 6-2	[8]
Lunar shuttle	LEO (@ 500 km, 45°)	LLO	3.3÷4.4	Vega C	[9]
	GTO	LLO	1.25÷1.75	Ariane 6-2	[8] [13]
Lunar lander	LEO (@ 500 km, 45°)	Lunar surface	5.3÷6.4	Vega C	[9][10]
	GTO	Lunar surface	3.25÷3.75	Ariane 6-2	[8] [10] [13]
Mars	GTO	Ballistic capture	3÷3.5	Ariane 6-2	[8][11][12]

Considering a launch onboard the Vega C and the typical ΔV to perform in-orbit servicing and operations in LEO, the payload mass transportable with the OPM is readable in the plot of Figure *4*. To each OPM configuration corresponds a curve. Starting from ΔV=0 km/s, i.e., no propellant mass onboard, the dashed line is obtained because of increasing propellant up to reaching the maximum loadable for the given OPM configuration. After this point, the continuous line represents the payload mass which can be obtained for higher ΔV requirements. Indeed, being the propellant mass and the inert mass fixed by the OPM architecture, the only way to reach higher velocity increments is by reducing the payload mass. Thus, the dashed line can be seen as a representation of the constraint on the total initial OPM mass equal to the maximum launcher payload: being the inert mass fixed, the increase in propellant mass corresponds to a reduction in payload. For the first half of the selected ΔV range, the OPM-2a is the most suitable solution, as it would guarantee up to almost 1900 kg of payload. As the required ΔV increases beyond 1.5 km/s, the costlier OPM-2b starts to pay off with a larger payload, up to over 1500 kg. Examples of IOS operations in LEO are depicted in Figure *5*.

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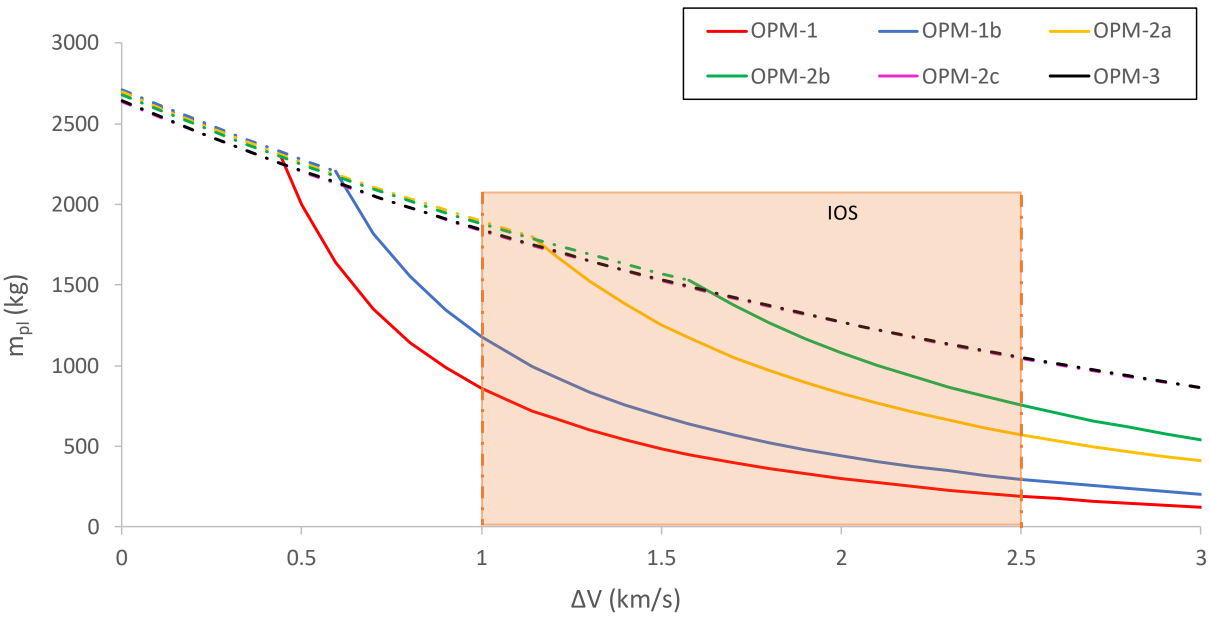

Figure 4: Payload mass vs ΔV, IOS with Vega C

Figure 5: Vertue OPM performing IOS on ENVISAT satellite (left) and deploying a Sentinel-class Earth observation satellites (right).

In Figure *6* the achievable payload mass curves for lunar shuttle and lunar lander missions with Vega C is depicted. Notice that:

- the extreme case ΔV=0, corresponds to a payload mass equal to the launcher payload reduced by the inert mass of the OPM.
- The change in slope along the continuous line (red circle in figure) corresponds to an increment in the inert mass due to the landing gear structure needed for the lunar descent mission.

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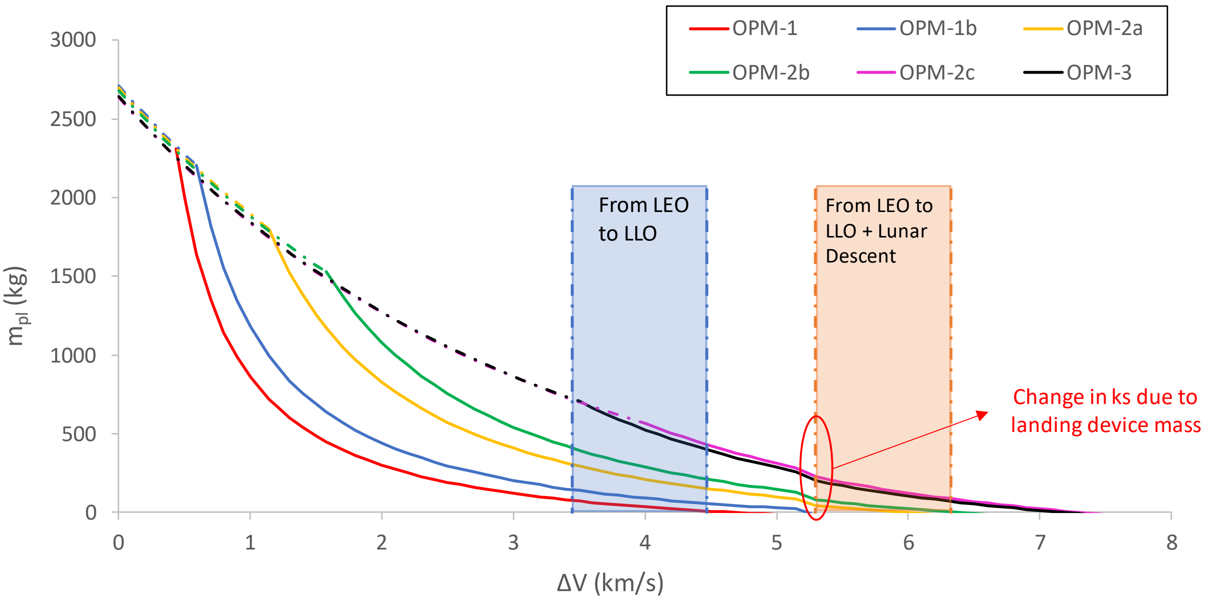

Figure 6: Payload mass vs ΔV, lunar shuttle and lunar lander missions with Vega C

In Figure *7* the payload mass is plotted against the structural efficiency for lunar shuttle and lunar lander missions with Vega C. For a given mission in terms of ΔV range, the payload mass achievable with the different OPM configurations is represented by the coloured regions in the plot. For instance, a transfer from LEO to LLO, i.e., lunar shuttle mission, is possible by any of the OPM configurations with the difference characterized by the lift-off mass. Instead, the lunar landing mission can be achieved only by the heavy-loading configurations (from OPM-2b on) with a satisfactory payload mass transferable onto the lunar surface. This highlights the extreme adaptability of the OPM to different mission requirements. OPM lunar missions are depicted in Figure *8*.

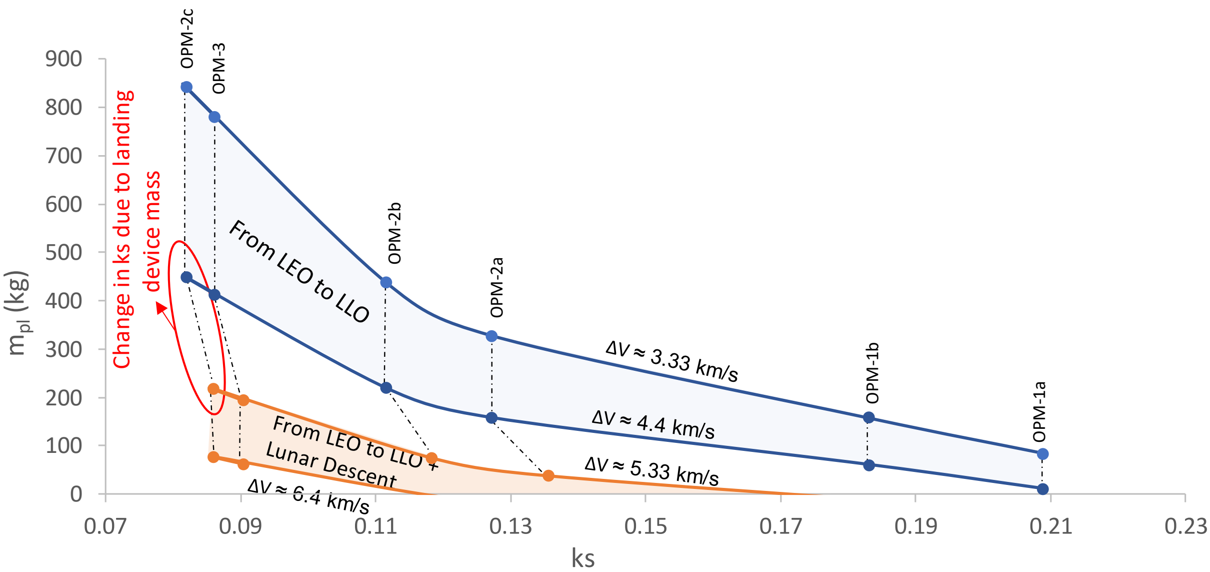

Figure 7: Payload mass vs structural efficiency, lunar shuttle and lunar lander missions with Vega C

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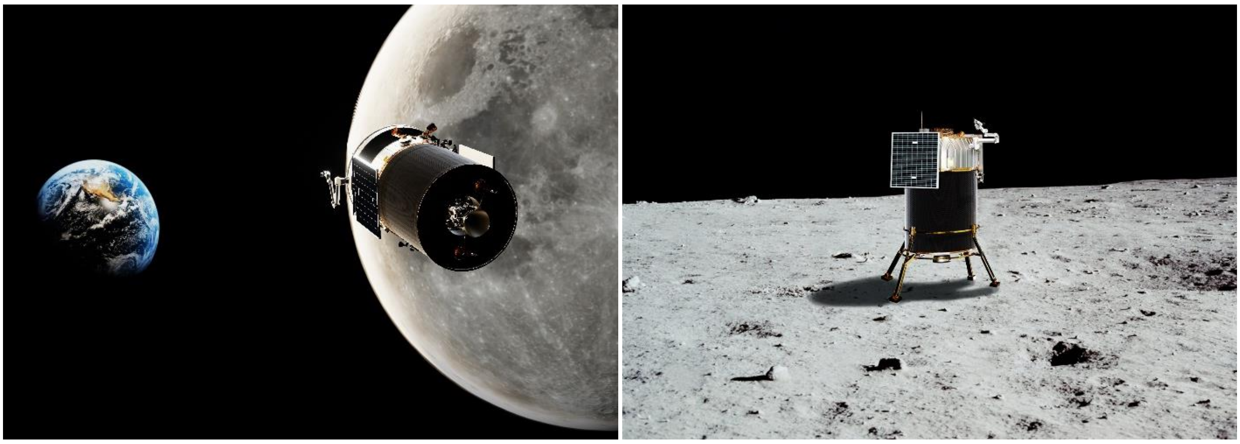

Figure 8: Use of Vertue OPM for lunar missions: lunar shuttle (left) and lunar lander (right).

The same results (lunar shuttle and lunar landing missions) are reported in Figure *9* and Figure *10* considering the Ariane 6-2 launcher inserting the OPM in GTO. Starting the transfer from GTO, which implies a reduced ΔV to reach LLO and the increased payload capacity of the launcher, result in noticeable increase in payload mass of the OPM with respect to the case described in Figure *6*. Again, the change in slope along the continuous line (red circle in figure) corresponds to an increment in the inert mass due to the landing gear structure needed for the lunar descent mission.

Looking at Figure *10*, one can notice that lunar landing missions, starting from GTO, are enabled by all the OPM configurations: from OPM-1a, at least 41 kg can reach the lunar surface.

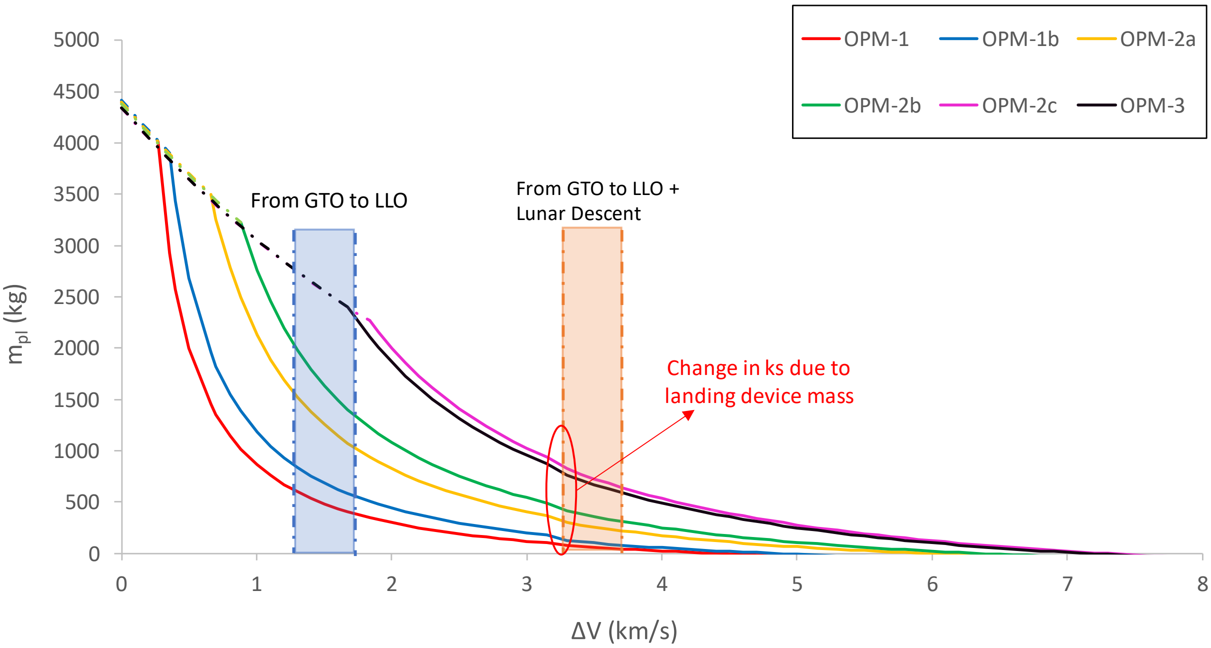

Figure 9: Payload mass vs ΔV, lunar shuttle and lunar lander missions with Ariane 6-2

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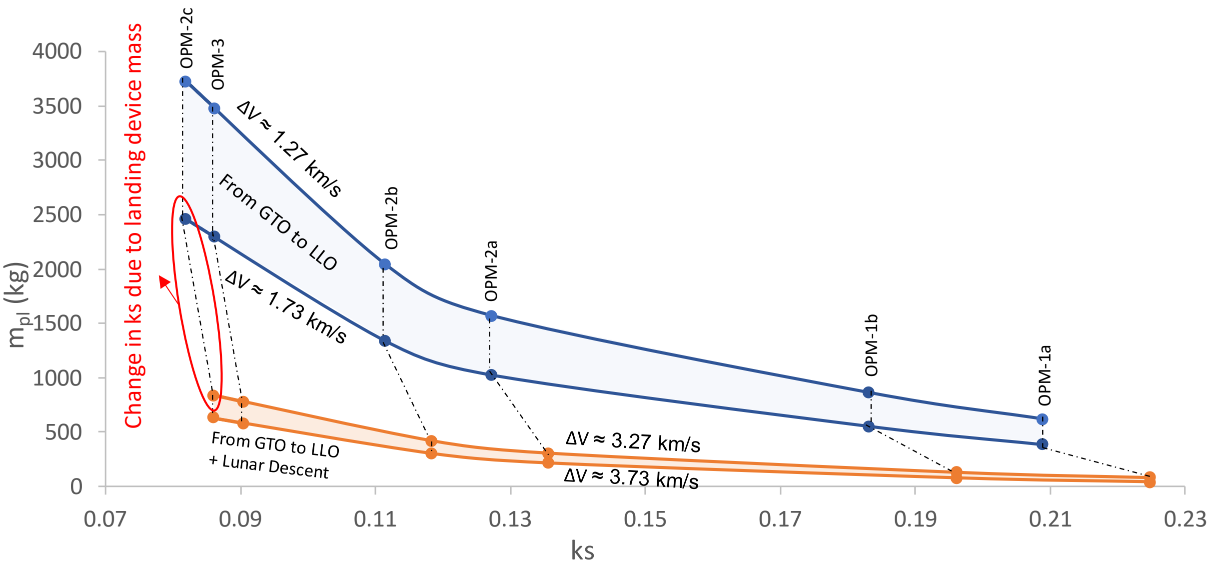

Figure 10: Payload mass vs structural efficiency, lunar shuttle and lunar lander missions with Ariane 6-2

Finally, considering a Mars ballistic capture mission from GTO with Ariane 6-2, results are reported in Figure *11* and Figure12. Up to 1000 kg can be captured by Mars with OPM-2c.

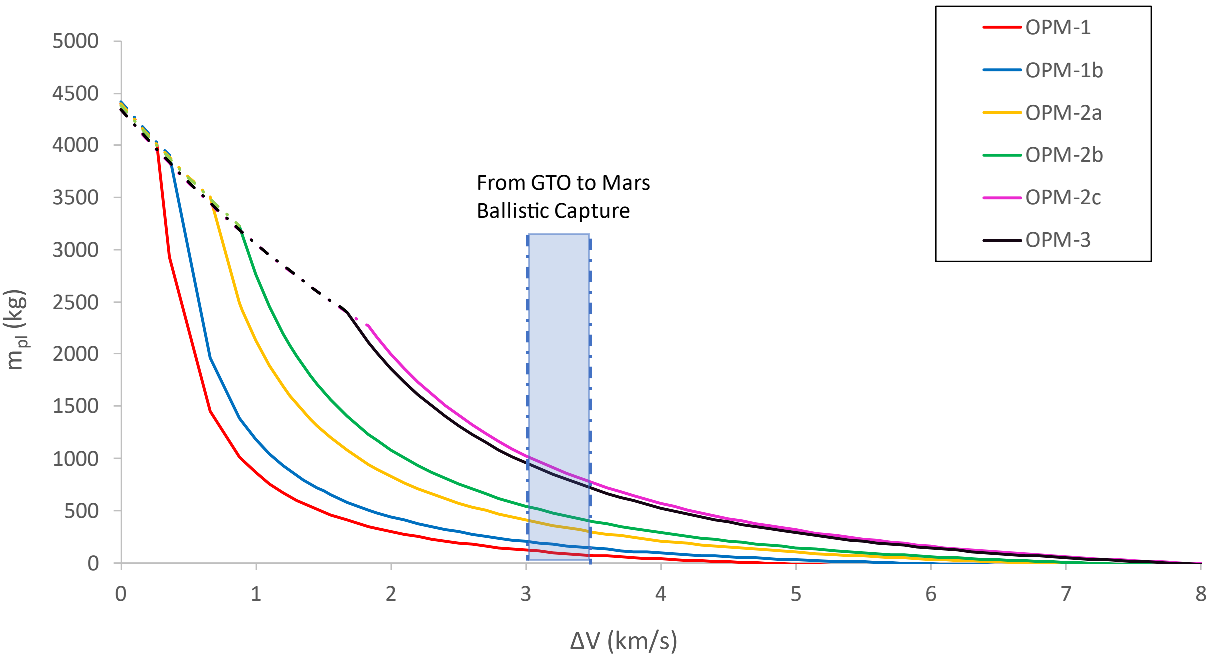

Figure 11: Payload mass vs ΔV, Mars missions with Ariane 6-2

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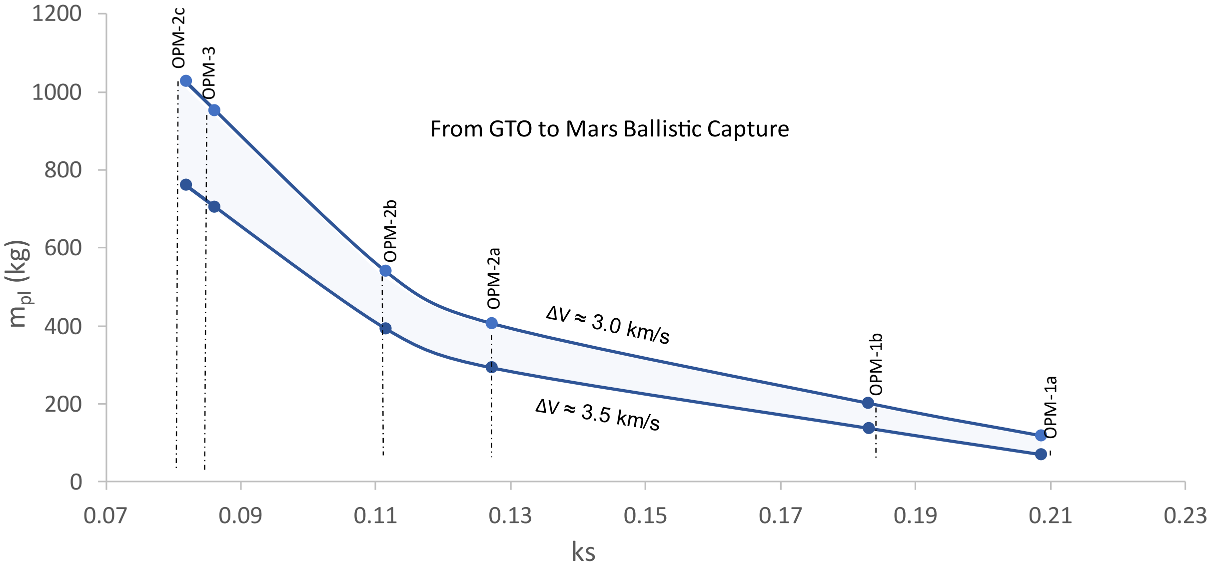

Figure12: Payload mass vs structural efficiency, Mars missions with Ariane 6-2

7. Conclusions

In the present work, an innovative solution for orbital space transportation – the Vertue Orbital Propulsion Module (OPM) - under development in Finis Terrae, has been presented. The architecture of OPM features unprecedented structural efficiency in the market, as a result of the toroidal-shaped integrated propellant tanks allowing a smart arrangement of inert masses and volumes. The OPM comes with a variety of sizes and propellant loadings to meet a range of customer requirements in terms of ΔV and payload mass, while ensuring compliance with standard payload adapters from available launchers in the market. The OPM solution enables operations in LEO (e.g., IOS missions) as well as deep-space missions to the Moon (with landing) and to Mars. It has been shown that launching onboard Vega C, the OPM could deliver up to 800 kg and over 200 kg to Low Lunar Orbit and to the lunar surface respectively, from LEO. Considering a launch onboard Ariane 6-2 and reaching the Moon from GTO with the OPM, the achievable payload mass improves to over 3000 kg (LLO) and almost 800 kg (lunar surface). With the same launcher, it is possible for a payload up to 1000 kg to be captured by the Martian sphere of influence, travelling onboard the OPM on a Mars-bound transfer from LEO. In conclusion, the Vertue OPM, when developed in accordance with technical, cost and market availability targets, could be the potential breakthrough in the orbital space transportation sector, becoming the world reference in the market.

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